The Leeuwin Current - observations and recent models

G R Cresswell

CSIRO Division of Oceanography, Hobart, Tas 7001, Australia

Abstract

The Leeuwin Current carries warm low salinity water from northwestern Australia into the prevailing equatorward wind to Cape Leeuwin and then across the Great Australian Bight. Current speeds to the west of the continent can exceed 0.5 ms^{-1}, while to the south they can exceed 1.5 ms^{-1}. In both regions the maximum speeds are encountered just beyond the continental shelf edge. Although the current is a low salinity feature to the west of the continent, once it rounds Cape Leeuwin it enters a regime of cold, low salinity waters so that it is then relatively high in salinity. The current frequently meanders and breaks out to sea forming both cyclonic and anticyclonic eddies. On its shoreward side it spreads across the continental shelf, commonly reaching the very near shore south of Western Australia. In this review a description of the Leeuwin Current is given by making use of observations ranging back to those of Flinders in 1803. Recent models of the current are found to be quite successful in describing many of its features.

Historical

If we define the Leeuwin Current (Church *et al.* 1989, Smith *et al.* 1991) as a stream of warm, low salinity water that flows at the surface from near NW Cape down to Cape Leeuwin and thence towards the Great Australian Bight (as suggested by the satellite image in Fig. 1), then we find evidence for it as early as the start of the last century. In May 1803 Flinders (1814) was set to the east between Cape Leeuwin and Albany at a little over one knot. Between Albany and the Recherche Archipelago (near Esperance) he reported the current to increase from the coast seaward. And "in coasting all around the Great Bight" he had no measurable current, suggesting, perhaps, that the current did not spread coastward across the wide continental shelf.

Along the west coast of Australia the earliest evidence for a current of tropical origin came from observations of warm waters and tropical marine flora and fauna around the Abrolhos Islands (~29°S) by naturalist Saville-Kent (1897). Also, early reports by fishermen described a southwards current between Geraldton and the Abrolhos Islands in winter which increased when northerly winds blew (Dakin 1919).

Halligan (1921) presented a chart of the currents around Australia (Fig. 2) and described how the warm comparatively light waters of the Indian Ocean would have to discharge to the south, since there is no northern outlet. With, as we will see, some precision, he described how a cold and heavy Southern Ocean current approached the south-west coast of Australia and dipped beneath the warm southerly drift. From the vicinity of Cape Leeuwin he reported "a warm southerly and easterly surface current" with speeds of 0.3 - 0.4 knots.

The August quarterly sea surface temperature map presented by Schott (1935) clearly showed warm waters (>16°C) to have been carried around Cape Leeuwin and eastward. This is reinforced by his winter (August-September) current chart (Fig. 3), which shows the Leeuwin Current more or less as we know it.

Southward flow of low salinity waters in autumn and winter and northward flow of high salinity waters in summer were seen from drift bottle measurements and hydrological observations by Rochford (1969).

Historical bathythermograph data were interpreted by Gentilli (1972) to show that the throughflow from the Pacific to the Indian Ocean in autumn and winter was isolated by a reversal of the flow in spring. This water then achieved thermal homogeneity over the summer to become a 'raft' of warm water, which spread southward during the following autumn and winter (Fig. 4). The 'raft' description was coined in the 1950's by Dr D L Serventy during discussions with fishermen who mentioned the warm water and the tropical species in it (Gentilli pers. comm. 1991).

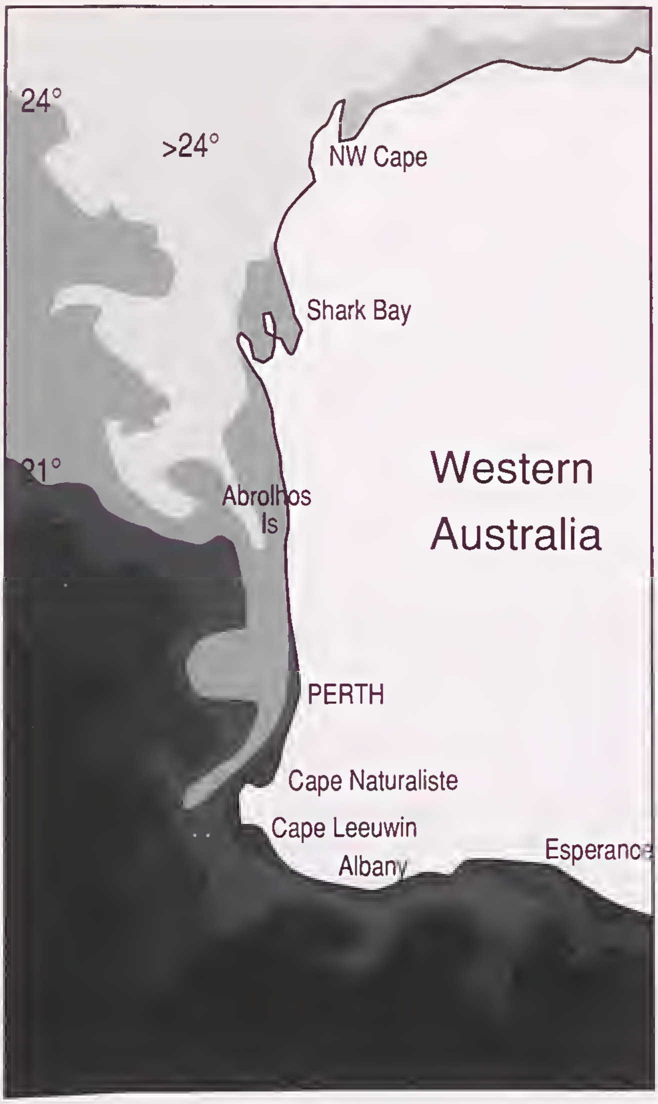

Figure 1 The temperature distribution off western Australia as determined from an infrared satellite image from 15 June 1984. The Leeuwin Current starts as a broad fan of warm water (>24°C) off the northwest and progresses southward to Cape Leeuwin and then eastward to the Great Australian Bight. There are eddies, meanders and offshoots associated with the Leeuwin Current. Mixing, radiation and evaporation change its water properties as it progresses.

Some fifteen years ago the response of satellite-tracked drifters (Cresswell & Golding 1980) to the flow of water of tropical origin was quite dramatic (Fig. 5), showing a drift to Cape Leeuwin and then eastward, as well as the interaction between this drift and the eddies offshore from it. Cresswell & Golding called the drift the Leeuwin Current, after the Leeuwin (Lioness in English), a Dutch ship that explored eastward towards the Bight in 1622.

The Leeuwin Current flows principally in autumn and winter. It is unusual in that it flows southward and into the wind. Other current systems on the eastern sides of oceans - the Benguela, Canary, Peru, and California current systems of the Atlantic and Pacific Oceans - flow equatorward. Further evidence for the Leeuwin Current from ship drift observations, research vessel surveys, and biological data sets is reviewed by Church *et al.* (1989) and Batteen & Rutherford (1990). In addition, analyses of the data from the Leeuwin Current Interdisciplinary Experiment (LUCIE) in 1986/87 are proceeding with some of the first findings being reported by Smith *et al.*(1991).

In the following sections we outline the features of the Leeuwin Current and the results of several conceptual and numerical models.

Features of the Leeuwin Current

Oceanic scale

It is instructive to take a large scale view of the salinity west of Australia in March along a line several hundred kilometres offshore running from Java to Antarctica (Fig. 6). Data collected by Deacon on RRS Discovery in 1936 and by Rochford on HMAS Gascoyne in 1963 have been combined - both were presented by Wyrtki (1971).

The section shows a number of interesting features:

- Near Java, there is low salinity water from river runoff and throughflow from the Pacific Ocean that tapers away to the south. Beneath the surface plume and down to the depth of the sill in the Timor Trench (about 1400m) are the near-constant salinity waters of the Banda Sea where they have had a residence time of some tens of years.
- Near Western Australia the excess of evaporation over precipitation produces dense salty South Indian Central Water that sinks and slowly moves northward.
- In the Southern Ocean, precipitation and ice melting result in a sinking plume of cold, fresh Antarctic Intermediate Water that also flows with a northward component .
- On the Antarctic continental shelf, where winter freezing excludes salt, there is a cold salty plume that sinks and moves northward as Antarctic Bottom Water. In summer, the surface water near Antarctica is warmed and it is diluted by ice melting. This produces the Antarctic Surface Water, which also moves northward.
- The southward-flowing Deep Water, which has its origins in the South Atlantic, replaces those northward flowing waters.

So then, where is the Leeuwin Current?

To see the current one must move closer to the continent - in autumn and winter when it flows strongest. The next diagram (Fig. 7) concentrates on the region from just north of NW Cape down to Cape Leeuwin - a voyage by HMAS Diamantina in August

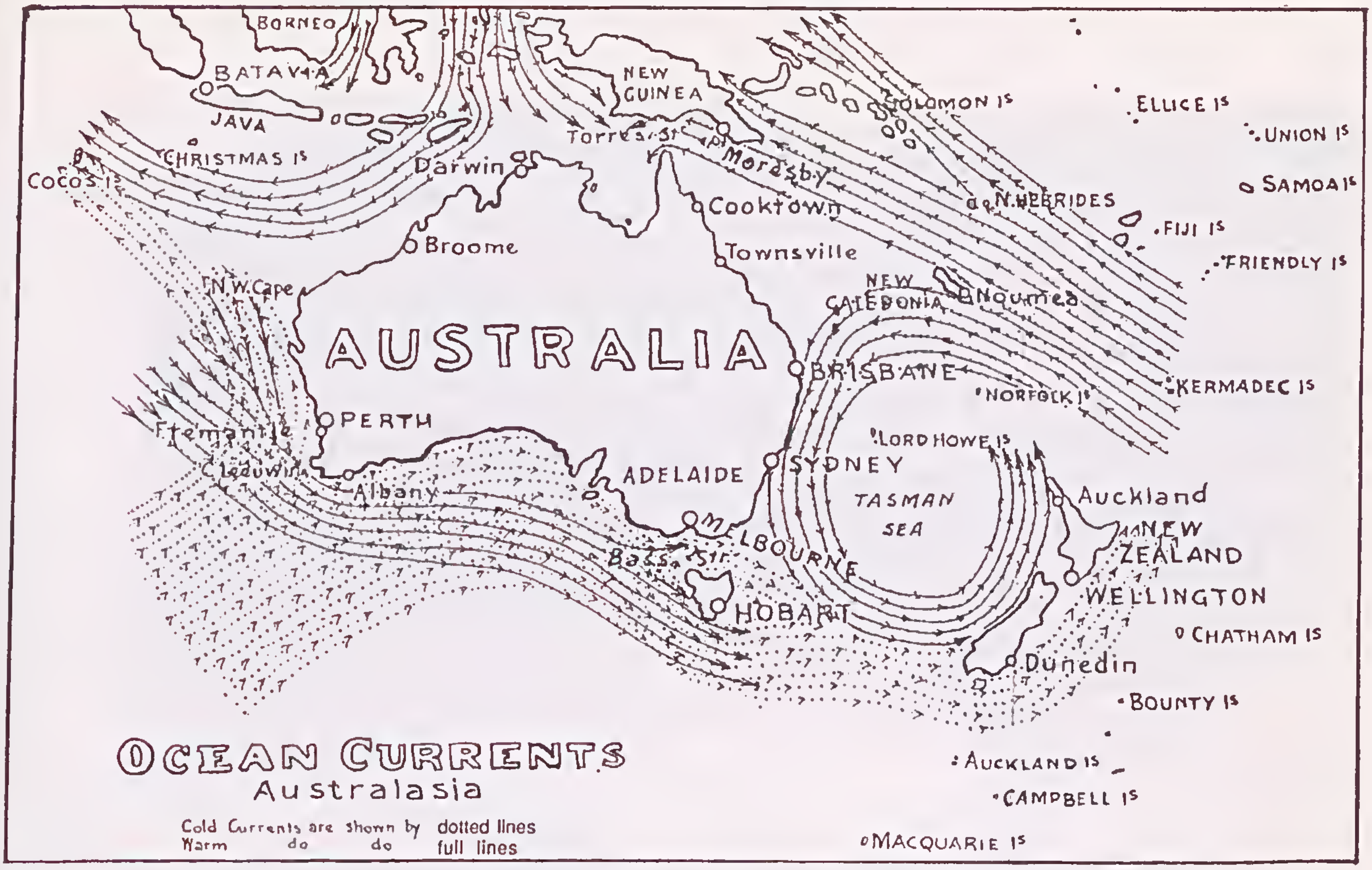

Figure 2 A current chart from Halligan (1921) showing a warm surface current flowing down the western Australian coast and a cold northward flowing current which sinks beneath it.

Figure 3 A current chart for the Australian region in winter (August-September) taken from a global chart by Schott (1935). The Leeuwin Current is readily apparent.

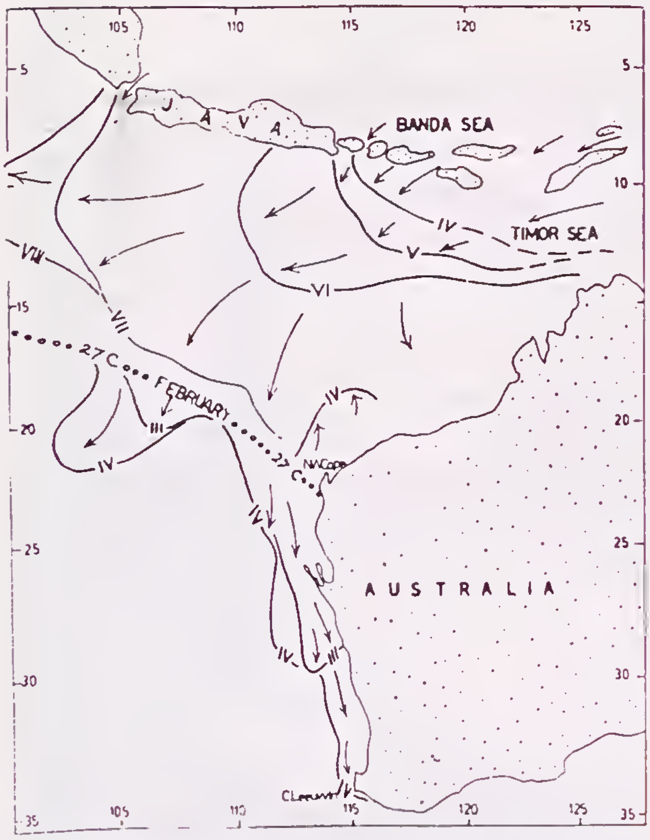

Figure 4 The position occupied by the 'raft' of warm water, originally from the throughflow, in February, followed by its progression to the south as the Leeuwin Current (from Gentilli 1972).

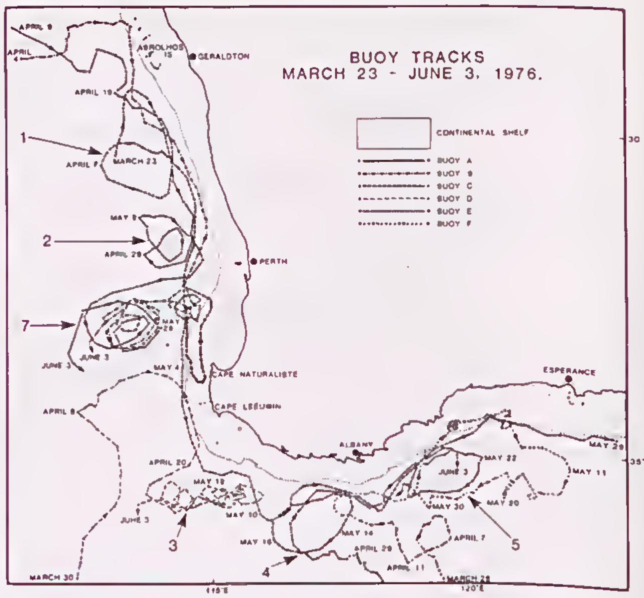

Figure 5 The tracks of the six drifters that were influenced by the Leeuwin Current or its associated cyclonic eddies (numbers 1-5) or the anticyclonic eddy (number 7) during the period March 23 to June 3, 1976 (from Cresswell & Golding 1980).

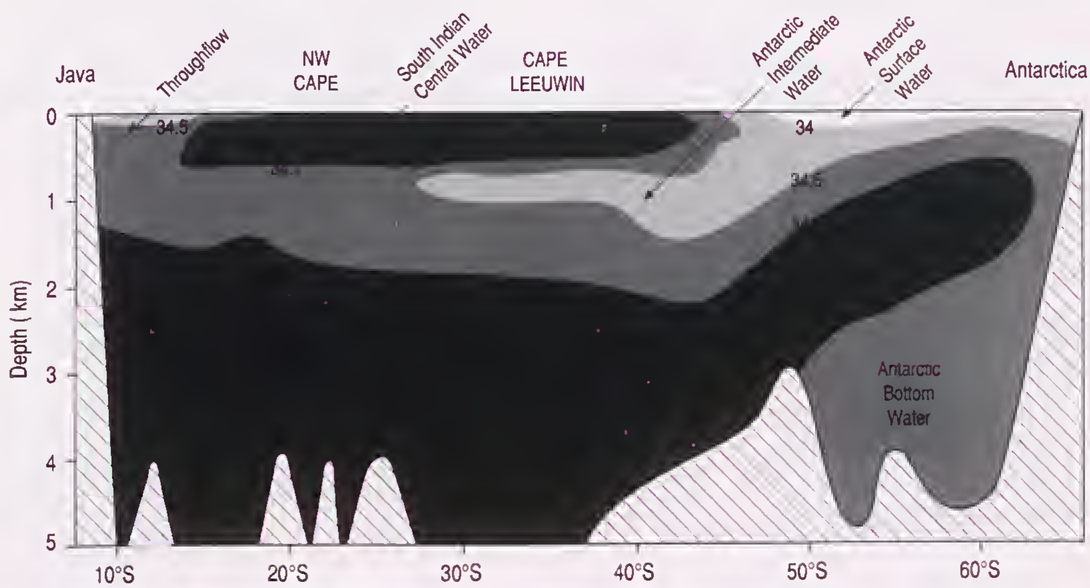

Figure 6 A salinity section looking towards Australia from several hundred kilometres offshore between Java and Antarctica. The data were collected by RRS Discovery in 1936 and HMAS Gascoyne in 1963 and presented by Wyrtki (1971). They were composited for this diagram.

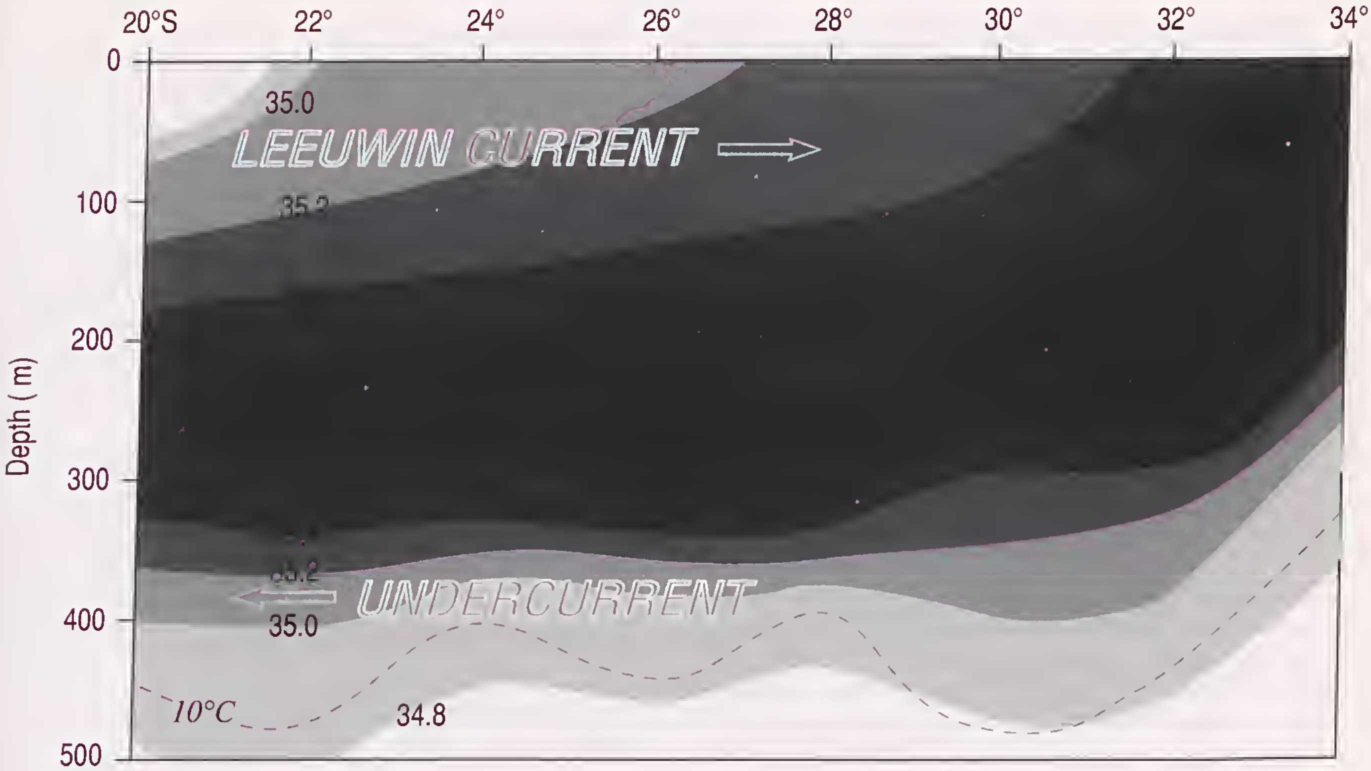

Figure 7 The salinity structure at the shelfedge and down the continental slope from NW Cape to Cape Leeuwin showing the low salinity Leeuwin Current and the Undercurrent, which carries South Indian Central Water and Subtropical Oxygen Maximum waters northward (from a cruise by HMAS Diamantina in August, 1971).

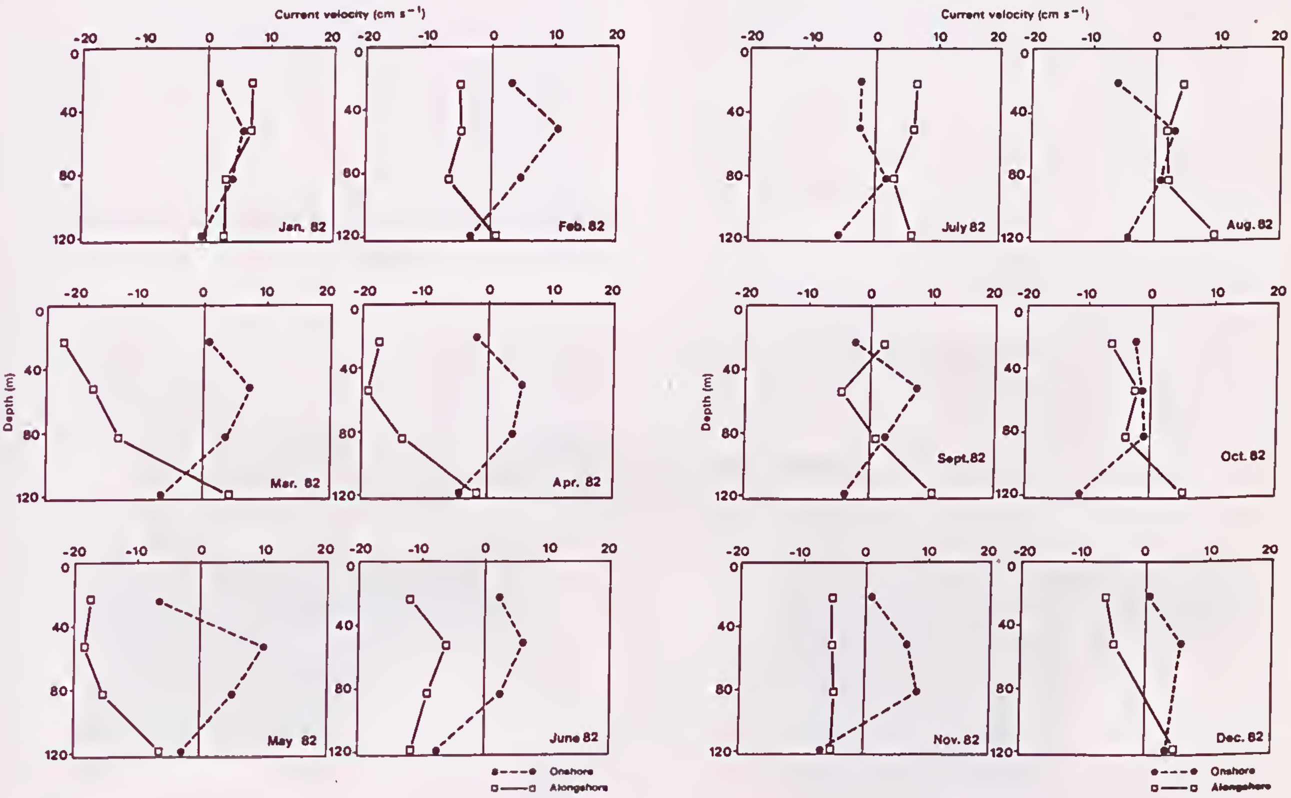

Figure 8 Vertical profiles of monthly average onshore and longshore currents measured at North Rankin (19° 35'S, 116° 05'E; water depth 123 m) on the southern NW Shelf in 1982. Negative alongshore currents represent southward flow and hence contribute to the Leeuwin Current (from Holloway & Nye 1985).

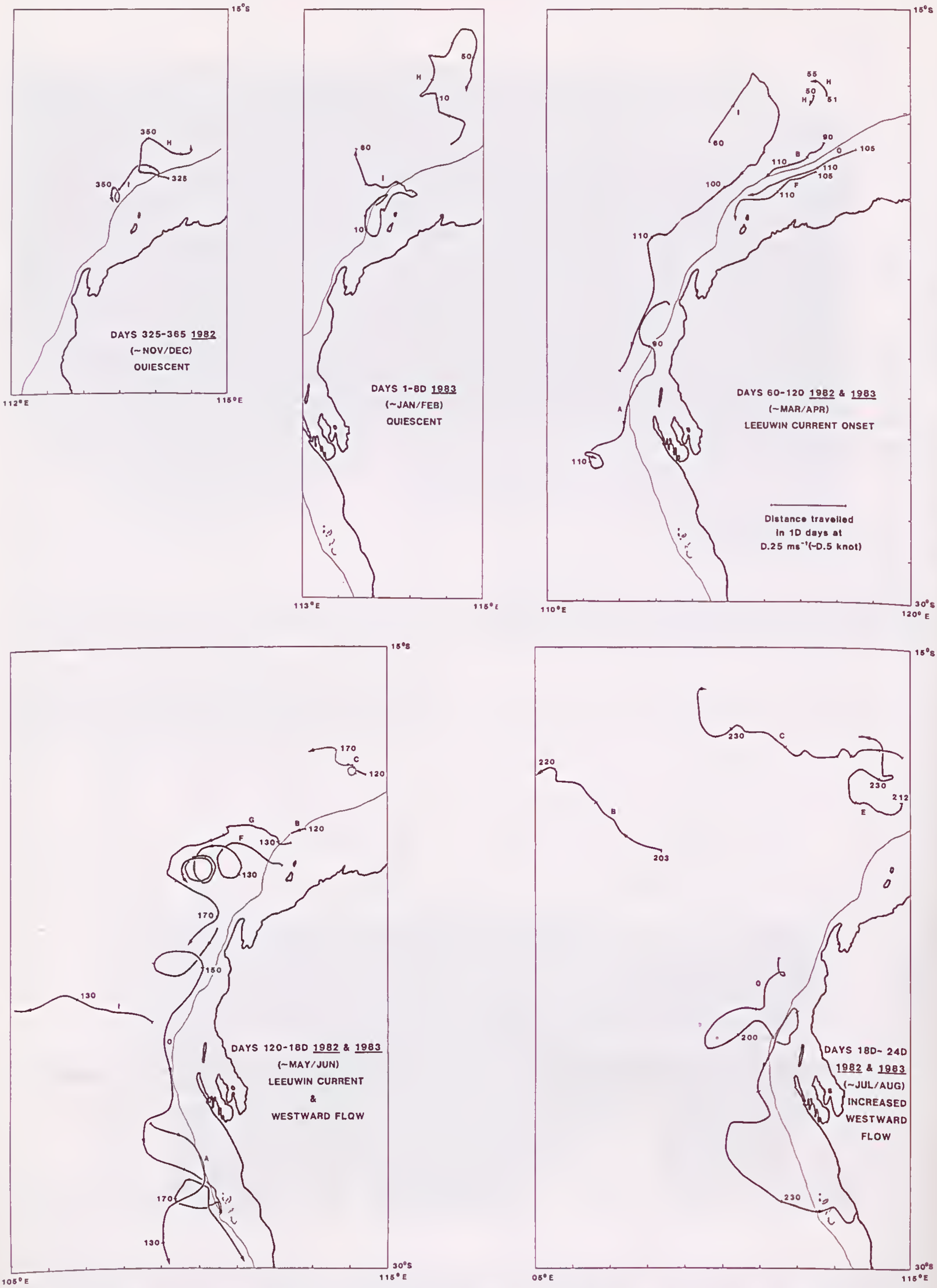

Figure 9 Satellite tracked drifters near and offshore from the Holloway and Nye (1985) moorings in 1982 and 1983 (see Figure 8).

1971. The diagram shows the salinity structure at the shelf edge and down the continental slope. The Leeuwin Current is the low salinity, warm wedge that extends southward to 30°S. Beneath it is the undercurrent sliding northward carrying high salinity South Indian Central Water as well as oxygen rich waters (not shown in this diagram). As the Leeuwin Current progresses southward it cools and becomes saltier because of evaporation and mixing with the South Indian Central Water.

Source

What is it that takes place at and south of the source area off NW Australia in autumn?

Current meter data for 1982/83 (Fig. 8) revealed a contribution to the Leeuwin Current by NW Shelf waters (Holloway & Nye 1985). It was strongest from February to June reaching 0.2 ms^{-1} in March-April-May in 1982.

Satellite tracked drifters near and offshore from the moorings in 1982 and 83 (Fig. 9) revealed an interesting seasonal behaviour:

> From November to late March the situation could best be described as quiescent, with the drifters moving slowly (~0.1 ms^{-1}) and following no consistent path.
>
> At the start of April, however, there was a dramatic move poleward at speeds of about 0.2 ms^{-1} on the shelf and up to 0.3 ms^{-1} off the shelf. A drifter that rounded NW Cape in late April accelerated to 0.5 ms^{-1}.
>
> May through August saw predominantly poleward flow with an increasing tendency for the region to feed the South Equatorial Current.

West coast

Off NW Cape the warm low salinity source of the Leeuwin Current is broad and shallow (400 km by 50 m), but in running southward it tapers to less than 100 km and deepens to more than 100 m, while having speeds that can exceed 1 knot. The warm low salinity waters carried by the Current (Fig. 10) are commonly encountered just beyond the continental shelf edge, but they can spread half way to the coast, except in summer when a wind-driven high salinity northward flow occupies most of the shelf. Incidentally, in summer there is a region of strong shear on the outer shelf between the northgoing shelf waters and the southgoing waters further out to sea (Cresswell & Golding 1980 - their Fig. 7).

A number of current meters moored mid-shelf off Dongara and Rottnest Island (near Perth) in the mid 70s (Fig. 11) indicate the influence of the Leeuwin Current flowing southward at ~0.2 ms^{-1} (Cresswell *et al.* 1989). At all times of the year the mid-shelf currents were strongly influenced by passing weather patterns (Fig. 12), which resulted in current variations of up to 0.5 ms^{-1} and sea level changes of about 30 cm. In summer, atmospheric troughs from the north interrupted the northward wind stress and allowed the shelf waters to move south. In winter, the passage of lows near and south of Cape Leeuwin gave rise to strong northwesterly winds that augmented the southward Leeuwin Current flow on the shelf.

South coast

The Current appears to take on a new character once it rounds Cape Leeuwin. It enters a regime where its salinity is higher than ambient, rather than the reverse as is the case west of the continent where it flows through high salinity South Indian Central Water. In the second (fresher) regime the Leeuwin Current has been observed to carry with it a sheath of salty South Indian Central Water. The sheath is then slowly lost downstream through energetic mixing with the fresher offshore waters (Cresswell & Peterson unpubl.).

It is just beyond the shelfedge between Cape Leeuwin and the Bight that the Leeuwin Current reaches its greatest speeds of more than 3 knots, or 1.5 ms^{-1} (Fig. 13). It is quite narrow, a band less than 20 km wide contains the speeds exceeding 1 knot (0.5 ms^{-1}). Across the shelf the currents range down from 0.5 ms^{-1}. The offshore edge is marked by a temperature front of several degrees Celsius.

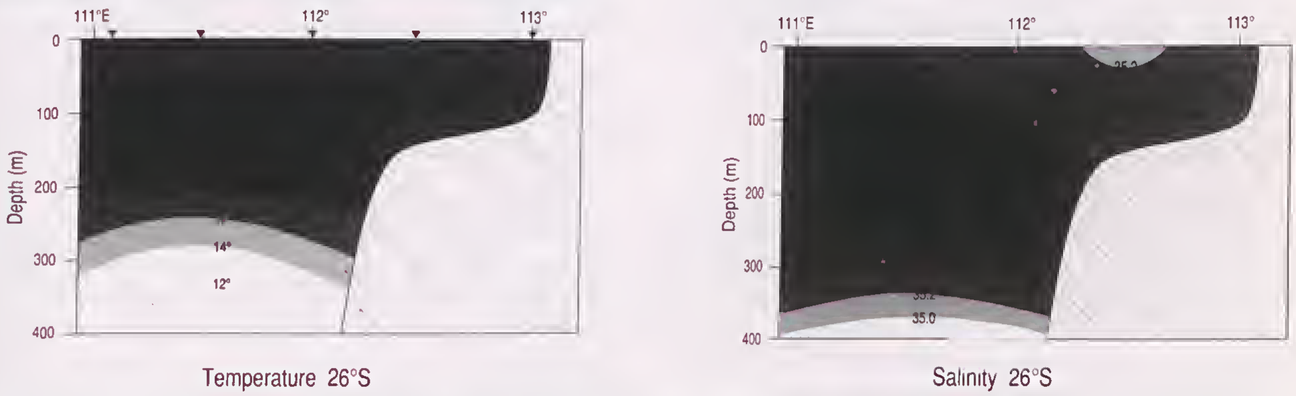

Figure 10 A section at 26°S made by HMAS Diamantina in August 1971 showing a) temperature and b) salinity.

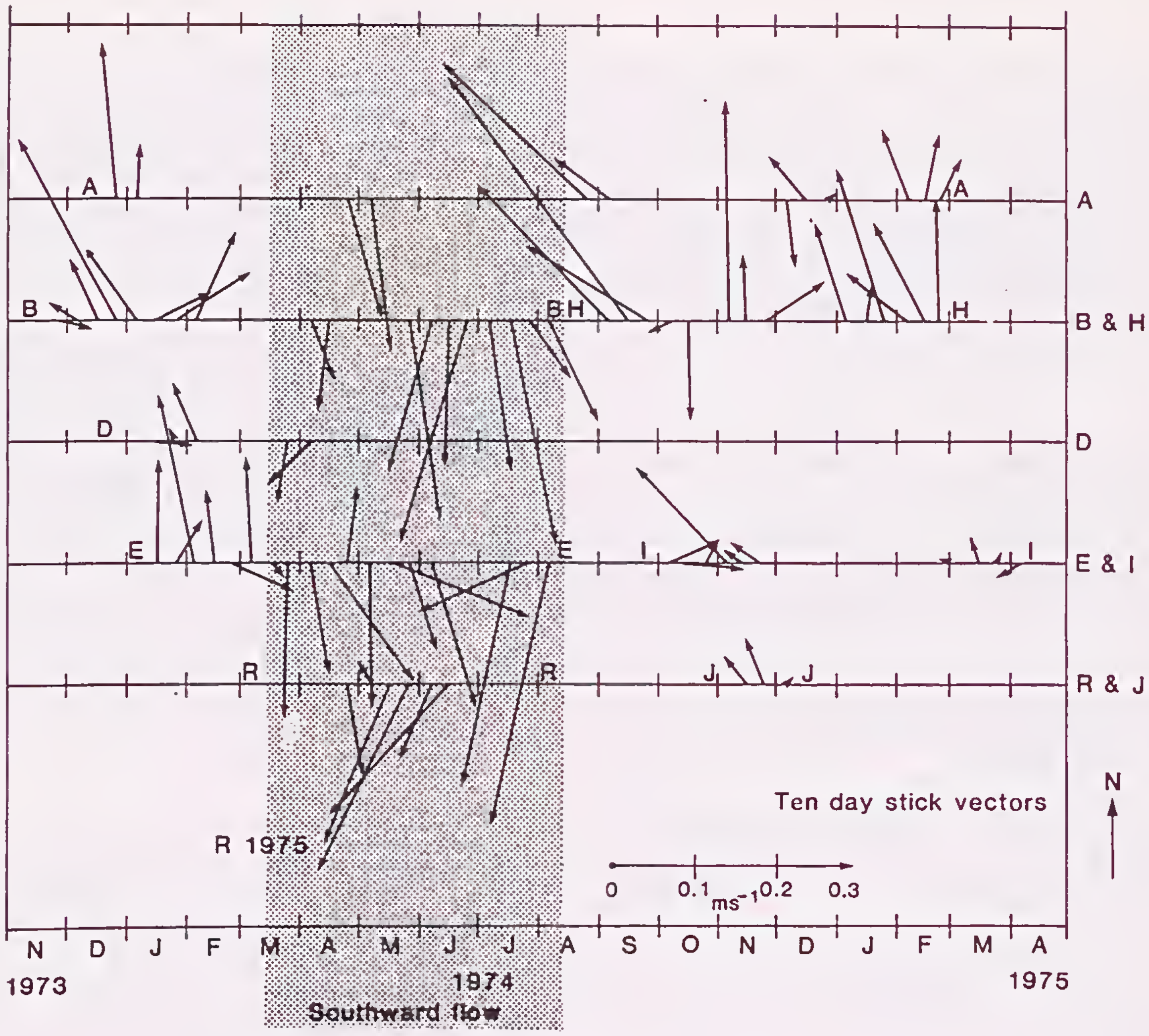

Figure 11 Current meter measurements from mid-shelf sites near the Abrolhos Islands (except for R which was near Rottnest Island off Perth) arranged according to site and time. The stick vectors are ten-day averages. The stippled period, from March to August, shows the period of strongest southward flow, probably the result of the Leeuwin Current spreading onto the shelf (from Cresswell *et al.* 1989).

There are places where the current breaks out to sea (Cresswell & Golding 1980, Griffiths & Pearce 1985) and in June 1987 it was found that one of the offshoots had a trough-shaped cross section 50 km wide by 150 m deep with southgoing flow on the western side and northgoing flow on the eastern side (Cresswell & Peterson unpubl.). Many features of the offshoots have been reproduced in rotating laboratory tanks (Condie & Ivey 1988).

Some attempts to explain the current

Thompson (1984, 1987) concluded that the Leeuwin Current is driven into the prevailing wind by a longshore sea-level gradient and further that the wind forcing effects are diminished by deep mixed layers. In other words, the force of the northward wind is distributed over considerable depth and is therefore less effective in retarding the southward flow.

Godfrey & Ridgway (1985) examined the annual cycles of sea level and wind stress (Fig. 14). The annual average sea level shows a southward flow component near the coast, as indicated by the orientation of the sea level contours, which increases in strength southward from NW Cape. The annual average wind stress is strongly northward between Cape Leeuwin and NW Cape. (Further north, the wind has a strong component to the west and this may explain why drifters in the near-surface layer moved off in that direction to join the South Equatorial Current.)

However, the wind stress eases between March and October to reinforce the effects of the peak in sea level difference at the shelf edge between NW Cape and Cape Leeuwin from February to August (Fig. 15). Incidentally, during LUCIE in 1986/87 the seasonal variation in the strength of the Leeuwin Current seemed to be the result of variations in the wind stress and not in the alongshore pressure gradient, which had little seasonal dependence (Smith *et al.* 1991).

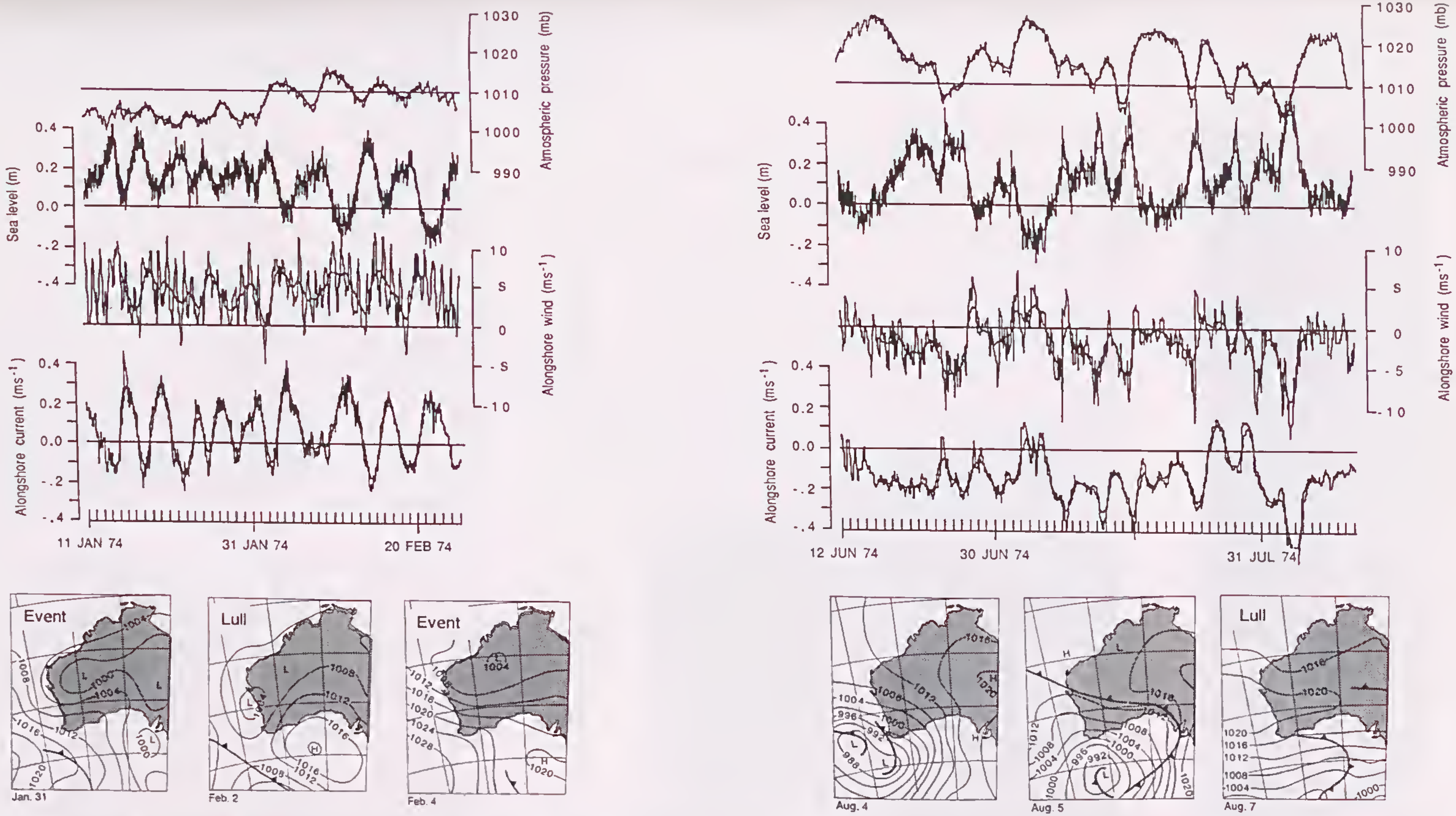

Figure 12 Time series of smoothed and unsmoothed atmospheric pressure, sea level (tides removed) and alongshore wind from Geraldton and the current 10 m above the bottom at a site near the Abrolhos Islands where the depth was 42 m in summer and 46m in winter (from Cresswell *et al.* 1989).

a) Summer (January/February). (Upper panel) The strong sea breeze has little effect on the currents at the depth of the current meter. However, when the winds are northward (positive) for several days the sealevel falls and the currents are northward. Low wind speeds produce elevated sea level and southward currents. (Lower panel) An example showing the synoptic atmospheric pressure charts for a period of low winds (Feb 2) that allows southward flow on the continental shelf. Before and after the winds have a southerly component that drives the flow northward.

b) Winter (June/August). (Upper panel) The current is predominantly southward due to the influence of the Leeuwin Current spreading onto the shelf. Winds with a strong southward component increase the current to almost 0.5 ms^{-1} and raise sea level by as much as 0.4 m. (Lower panel) An example of the synoptic atmospheric pressure charts at a time of enhanced southward flow on August 4/5.

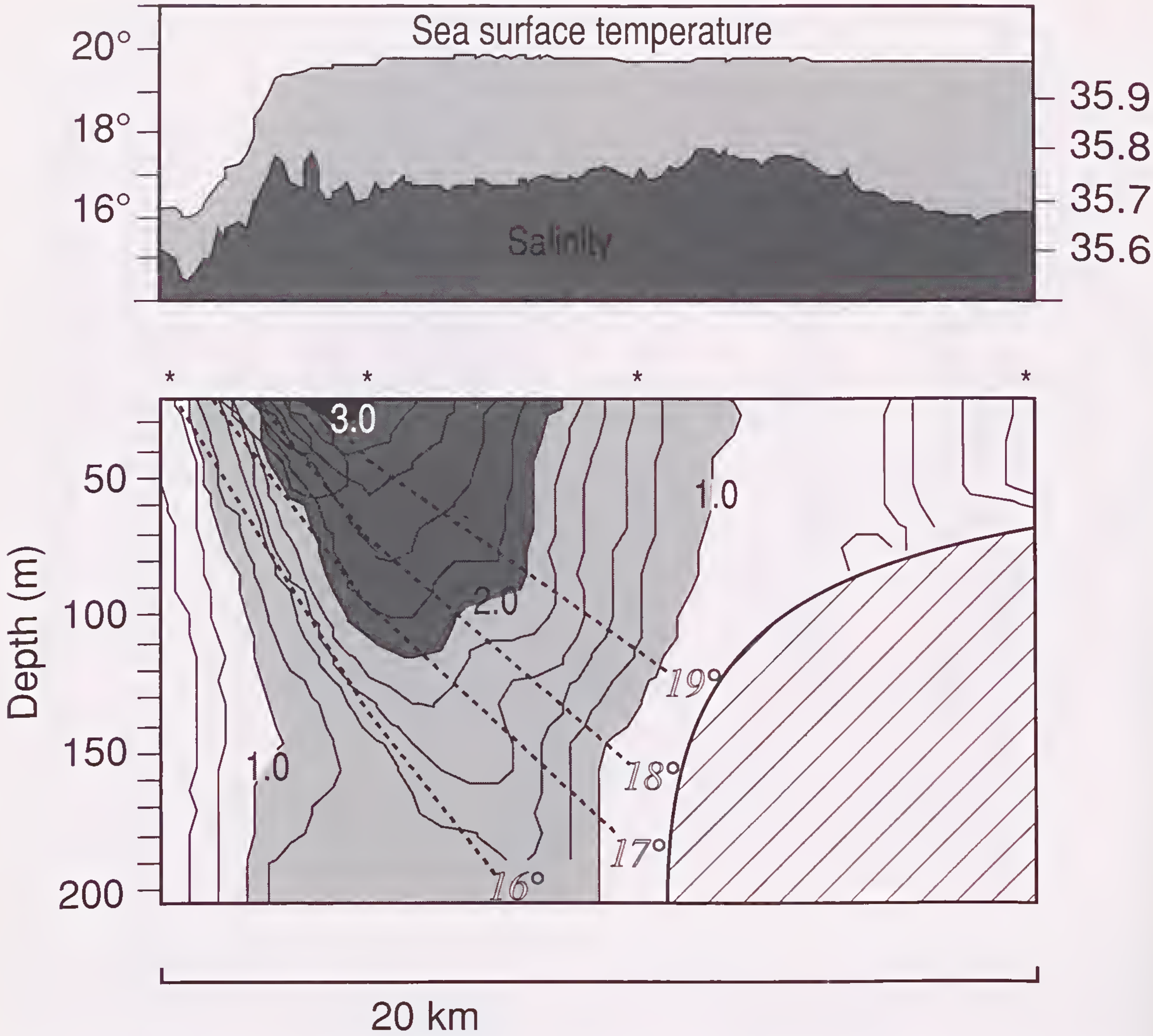

Figure 13 A section (bottom panel) showing the current structure measured by RV Franklin along a line out from the coast west of Albany in June 1987. Current speeds greater than 1.0, 2.0 and 3.0 knots have progressively darker shading. The isotherms measured by expendable temperature probes are shown. Note the surface temperature and salinity front (top panel) on the offshore edge of the Leeuwin Current where the speed dramatically decreases and where considerable overturn and mixing take place.

Weaver & Middleton (1989) used the Bryan-Cox General Ocean Circulation Model with seven vertical levels and initial conditions of a latitudinal variation of temperature and salinity. In addition, taking a lead from Gentilli's (1972) suggestion of a raft of warm water off NW Australia, they took all the water in the triangle east and north of NW Cape to have warm, less saline NW Shelf waters (28.3°C and 34.3ppt at the surface). They also allowed for a shelf that tapered from north to south along the WA coast. After running for 30 days, their model (Fig. 16) reproduced both the Leeuwin Current and the Undercurrent quite well -even to the extent of rounding Cape Leeuwin and flowing to the east.

Batteen & Rutherford (1990) developed a ten-layer model of the ocean between NW Cape and Cape Leeuwin using a climatological mean density and (in an alternative approach) included an input of water from the NW Shelf. In the latter case, as time passed the nature of the ocean temperature and sea level evolved from their initial setup in response to earth's rotation, eddy viscosity and bottom stress. After a time step of only ten days a Leeuwin Current had been established (Fig. 17). After much longer, an anticyclonic eddy formed off Perth, while north of it was a weaker cyclonic eddy. Both are reminiscent of the features revealed by the drifter tracks and ship data (Andrews 1977, Cresswell 1977).

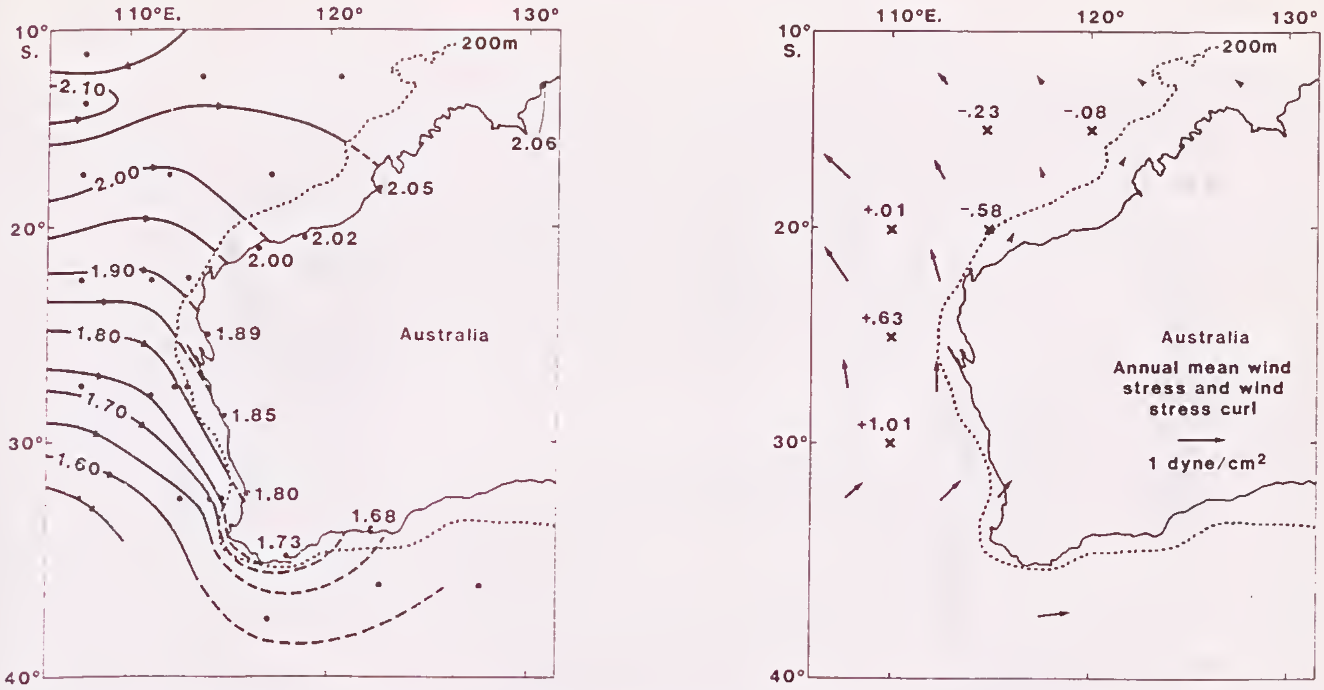

Figure 14 a) Contours of annual average steric sea level relative to 1300 db. The numbers along the coast give mean sea level at tide gauge locations. b) Annual average wind stress and wind stress curl (from Godfrey & Ridgway 1985).

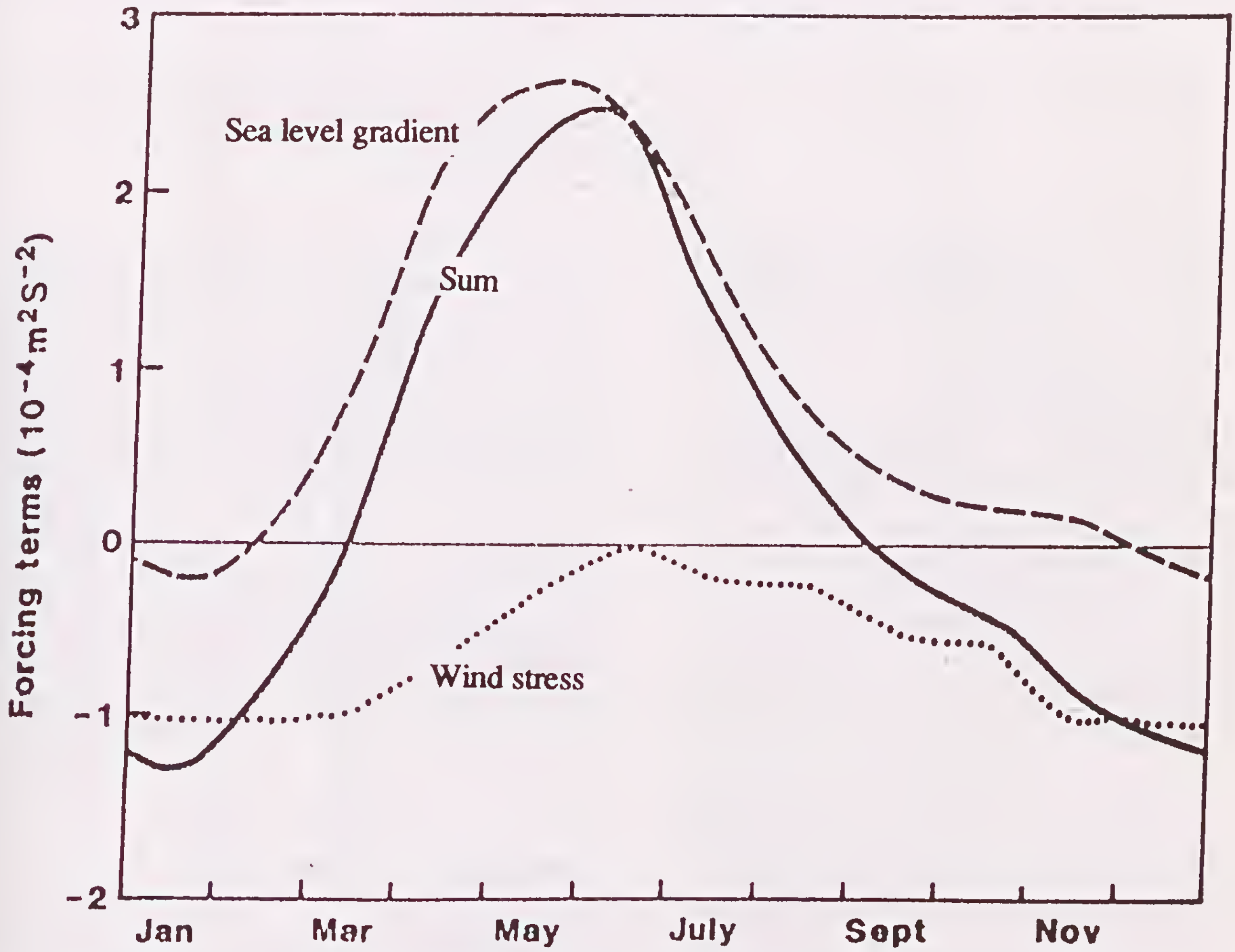

Figure 15 The annual cycle of the sum of the forces which drive and retard the Leeuwin Current (full line). These are the sea level gradient (dashed line) and the wind stress (dotted line) (from Godfrey & Ridgway 1985).

Surface current after 30 days

350 m current after 30 days

Surface temperature after 30 days

Figure 16 The output from the model of Weaver & Middleton (1989) after it had run for 30 days. The Leeuwin Current can be seen rounding Cape Leeuwin in the representation of both the surface current (left panel) and surface temperature (right panel). The undercurrent can be seen at 350 m (middle panel).

Surface temperature and current

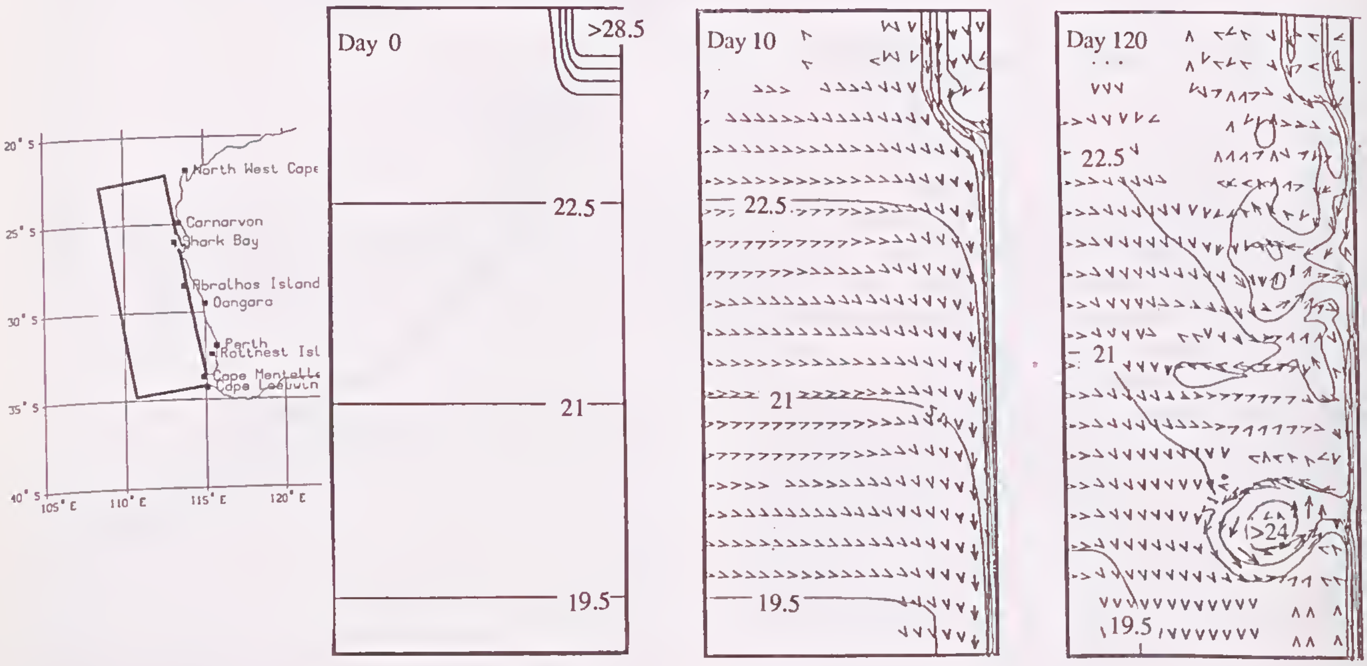

Figure 17a The initial conditions and selected results, at days 10 and 120, for surface temperature and surface currents from the model of Batteen & Rutherford (1990). The current speeds in the anticyclonic eddy off Perth are about 0.5 ms^{-1}.

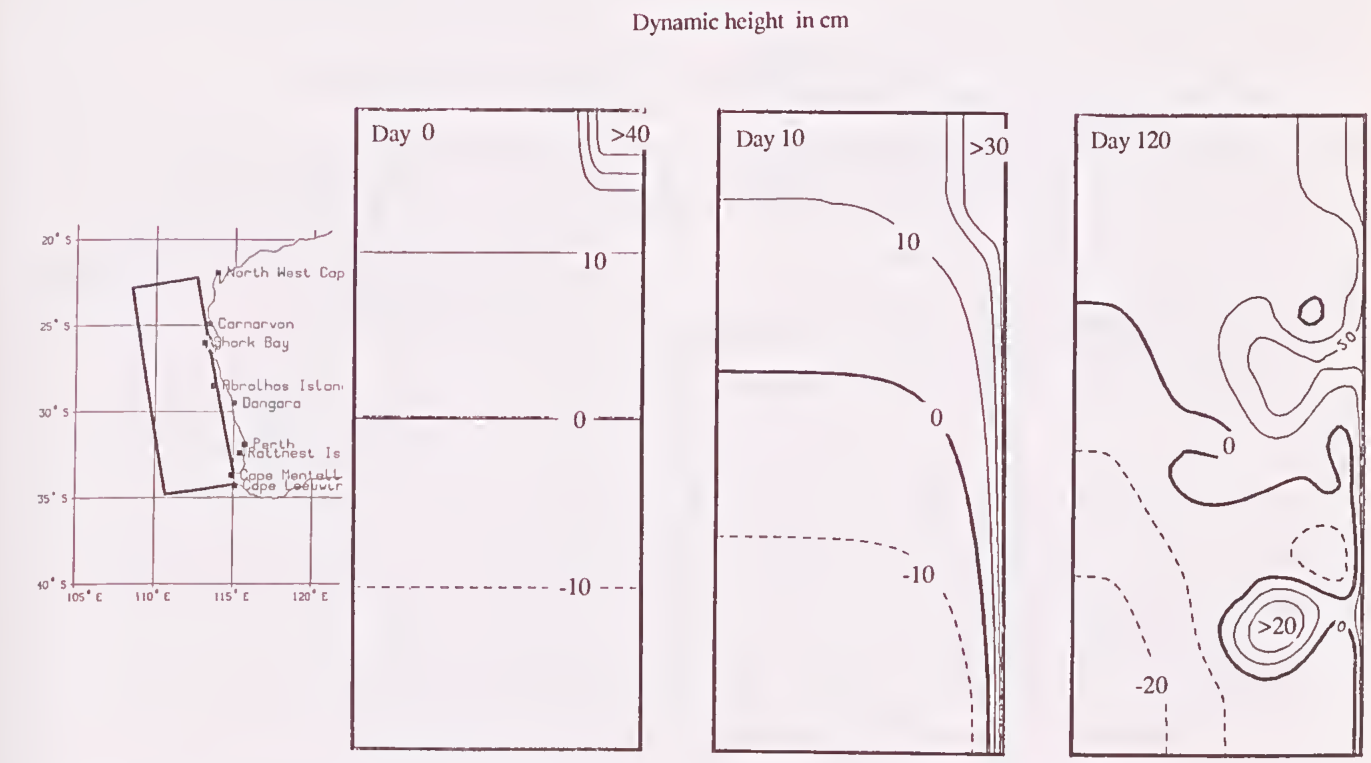

Figure 17b The initial conditions and selected results, at days 10 and 120, for dynamic height from the model of Batteen & Rutherford (1990). The current speeds in the anticyclonic eddy off Perth are about 0.5 ms^{-1}.

Concluding comments

Models now reproduce many of the features of the Leeuwin Current, such as rounding Cape Leeuwin, having an undercurrent and generating eddies. However, the challenge of developing a model which will produce the annual and interannual variations of the Leeuwin Current remains. Also, such a model will ideally need to mesh in with models of continental shelf circulation.

The immediate future will see the launching of satellites such as ERS-1 and TOPEX/POSEIDON which are capable of measuring sea surface elevation, roughness and winds. This information will be used along with ship, drifter and tidal data to constantly update models, rather than have them rely on climatological means.

References

Andrews J C 1977 Eddy structure and the West Australian Current. Deep-Sea Res 24: 1133-48.

Batteen M L & Rutherford M J 1990 Modeling studies of eddies in the Leeuwin Current: The role of thermal forcing. J Phys Oceanogr 20: 1484-1520.

Church J A, Cresswell G R & Godfrey J S 1989 The Leeuwin Current. In: Poleward Flows along Eastern Ocean Boundaries. (eds S Neshyba, C N K Mooers & R L Smith). Springer-Verlag New York Inc 374 pp.

Condie S A & Ivey G N 1988 Convectively driven coastal currents in a rotating basin. J Mar Res 46: 473-494.

Cresswell G R 1977 The trapping of two drifting buoys by an ocean eddy. Deep-Sea Res 24: 1203-09.

Cresswell G R & Golding T J 1980 Observations of a south-flowing current in the southeastern Indian Ocean. Deep-Sea Res 27A: 449-466.

Cresswell G R, Boland F M, Peterson J L & Wells G S 1989 Continental shelf currents near the Abrolhos Islands Western Australia. Aust J Mar Freshw Res 40: 113-128.

Dakin W J 1919 The Percy Sladen Trust Expeditions to the Abrolhos Islands (Indian Ocean). Report I. J Linn Soc 34: 127-180.

Flinders M 1814 A voyage to Terra Australis. Vol I: 269pp, Vol II: 613pp Nicol London (1966 Facsimile Edition) Library Board of South Australia.

Gentilli J 1972 Thermal anomalies in the Eastern Indian Ocean. Nature 238: Physical Sciences 93-95.

Godfrey J S & Ridgway K R 1985 The large-scale environment of the poleward-flowing Leeuwin Current, Western Australia: longshore steric height gradients, wind stresses and geostrophic flow. J Phys Oceanogr 15: 481-495.

Griffiths R W & Pearce A F 1985 Instability and eddy pairs on the Leeuwin Current south of Australia. Deep-Sea Res 32: 1511-34.

Halligan G H 1921 The ocean currents around Australia. J Roy Soc N S W 55: 188-195.

Holloway P E & Nye H C 1985 Leeuwin Current and wind distributions on the southern part of the Australian North West Shelf between January 1982 and July 1983. Aust J Mar Freshw Res 36: 123-37.

Rochford D J 1969 Seasonal interchange of high and low salinity surface waters off South-west Australia. CSIRO Division of Fisheries & Oceanography Technical Paper No 29.

Saville Kent W 1897 The naturalist in Australia. Chapman & Hall London.

Schott G 1935 Geographie des Indischen und Stillen Ozeans. Verlag von C Boysen Hamburg: 413pp.

Smith R L, Huyer A, Godfrey J S & Church J A 1991 The Leeuwin Current off Western Australia, 1986-1987. J Phys Oceanogr 21: 323-345.

Thompson R O R Y 1984 Observations of the Leeuwin Current off Western Australia. J Phys Oceanogr 14: 623-628.

Thompson R O R Y 1987 Continental shelf-scale model of the Leeuwin Current. J Mar Res 45: 813-827.

Weaver A J & Middleton J H 1989 On the dynamics of the Leeuwin Current. J Phys Oceanogr 19: 626-648.

Wyrtki K 1971 Oceanographic atlas of the International Indian Ocean Expedition. US Government Printing Office Washington 531pp.